

# FORWARD MONTECARLO COMPUTATIONS OF POLARIZED MICROWAVE RADIATION

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## 1. INTRODUCTION

Microwave radiative transfer computations continue to acquire greater importance as the emphasis in remote sensing shifts towards the understanding of microphysical properties of clouds and with these to better understand the non linear relation between rainfall rates and satellite-observed radiance.

A first step toward realistic radiative simulations has been the introduction of techniques capable of treating 3-dimensional geometry being generated by ever more sophisticated cloud resolving models. To date, a series of numerical codes have been developed to treat spherical and randomly oriented axisymmetric particles. Backward and backward-forward Monte Carlo methods are, indeed, efficient in this field, e.g. Roberti et al. (1999) Liu et al. (1996).

These methods, however, cannot deal properly with oriented particles, which seem to play an important role in polarization signatures over stratiform precipitation, see Heymsfield et al. (1996). Moreover, beyond the polarization channel, the next generation of fully polarimetric radiometers challenges us to better understand the behavior of the last two Stokes parameters as well.

In order to solve the vector radiative transfer equation, one-dimensional numerical models (e.g., Czekala et al. (1998), Evans et al. (1995), Wauben et al. (1992)) have been developed. These codes, unfortunately, consider the atmosphere as horizontally homogeneous with horizontally infinite plane parallel layers.

The next development step for microwave radiative transfer codes must be fully polarized 3-D methods. Recently Haferman et al. (1997) presented a 3-D polarized radiative transfer model based on the discrete ordinate method. Roberti and Kummerow (1999) developed a forward MC code that treats oriented non-spherical hydrometeors, but only for plane-parallel situations.

In this work, a 3-D forward Monte Carlo radiative transfer model for all 4 Stokes vector components has been developed in order to study the radiative properties of 3-D clouds containing non spherical water and ice particles; rather than adopting one of a host of backward, and backward-forward methods, this code is geared at the simplicity which can be gained from a pure forward model. In exchange for the simplicity, a fairly substantial computational penalty is payed, but the problem is manageable for microwave problems due to the relatively low optical depths in this region of the electromagnetic spectrum.

## 2. THE MONTE CARLO CODE

In the forward approach, photons are started from a scene in proportion to the total irradiance originating from each component of that scene (e.g. surface, atmosphere). The scene has to be taken large enough to cover all the regions from which photons are expected to arrive at the reception sensor and it is modeled with horizontally finite and vertically layered sub-clouds. A background plane parallel atmosphere then surrounds the cloud itself. Scattering properties - extinction and albedo (at different incident angles) and phase functions (at different incident and scattering angles) are computed for each finite cell as well as the plane parallel background.

Photons are released with the appropriate emission Stokes vector and are then traced forward using the usual random number techniques to simulate the distance of collision and the scattered direction. The photons' Stokes vector is multiplied by statistical weighting matrix to force all photons into scattering events only, thus avoiding absorption. This procedure further acts to remove statistical perturbation introduced by sampling the distance to collision from a biased probability distribution (Roberti (1999)). Scattering events are treated by sampling the outgoing direction randomly in the solid angle, computing the phase matrix (by interpolation from precomputed values) and multiplying the Stokes vector for a renormalised

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scattering matrix (Chuah et al. (1989)). A good crosscheck for this technique is the average conservation of intensity in scattering events.

The process is tracked until either the intensity has become so weak that its contribution to the next scattering is negligible or until the photon is scattered out of the cloud.

Rayleigh-Jeans brightness temperatures have been computed at the top and at the bottom of the atmosphere. Brightness temperatures, however, can also be computed at any position within the cloud to accommodate aircraft radiometer studies.

Computational requirements remain a concern. This code is therefore structured primarily to provide a simple framework in which to test the effect of various issues associated with oriented particles. Even so, results with adequate accuracy can generally be obtained within a few hours on today's workstations if the optical thickness of the analyzed scene remains in the order of magnitude of 1.

## 2.1 VALIDATION OF THE MODEL

The model has been validated in its full Stokes treatment by comparing its results with benchmark results from Haferman et al. (1996) and from Wauben et al. (1992) and in its 3D version by comparisons with Roberti et al. (1999).

An example of validation is given in fig. 1: the fluctuation introduced by the Monte Carlo statistics is self evident.

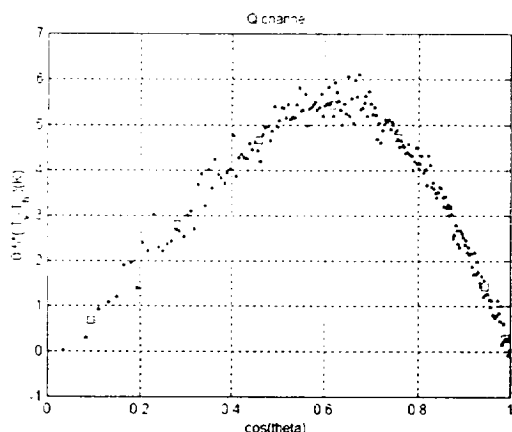


Figure 1: Comparison between upward polarization results from our code (dots) and from Haferman et al. (squares) for a two layer infinite atmosphere with ice and rain.

## 3. RESULTS

The radiative transfer simulations are carried out assuming both land and water surfaces because of their marked contrast in microwave radiometric properties: the land is modeled as a Lambertian surface with constant emissivity while the water is modeled as a Fresnel reflecting surface with the index of refraction of water varying with frequency, salinity, surface wind and temperature.

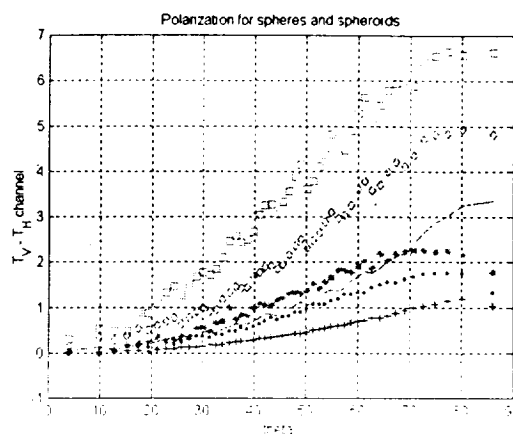


Figure 2: Upwelling polarization over Lambertian surface: +, • and \* line are for spheres while continuous, \$\diamond\$ and line for spheroids perfectly oriented correspondent to RR=5, 10, 20 mm/hr respectively.

As a simple example, a plane parallel 4-km layer of rain, modeled as a Marshall Palmer size distribution of prolate spheroids (with an axial ratio varying with size according to the literature), has been studied. Some results are presented at 19 GHz, although computations have been performed at 37 and 85 GHz also. At this frequencies a rainfall rate of 10 mm/hr corresponds to an optical thickness  $\tau=0.8$  and an albedo  $\omega=0.18$  while a rainfall rate of 20mm/hr corresponds to  $\tau=1.7$  and an albedo  $\omega=0.22$ .

Computed intensities (not shown), follow the general behavior that is expected: upwelling  $T_B$ , over sea (cold) surfaces increases with increasing rain rates, reach a maximum and decreases for higher rain rates. Increasing cloud emissivity, and thus the upward shift of the layer that contributes most to the radiance causes the decrease. For land (warm) surfaces the increasing effect is practically absent.

Stronger and more detectable differences can be observed in the polarization signal  $T_V - T_H = 2Q$  (see figs.2-4). For spheres, the radiation shows a positive polarization difference both upwelling and downwelling in the expected ranges. The effect is caused by the

symmetry breaking due to the finite vertical against the infinite horizontal dimension (e.g. Liu et al. 1996)

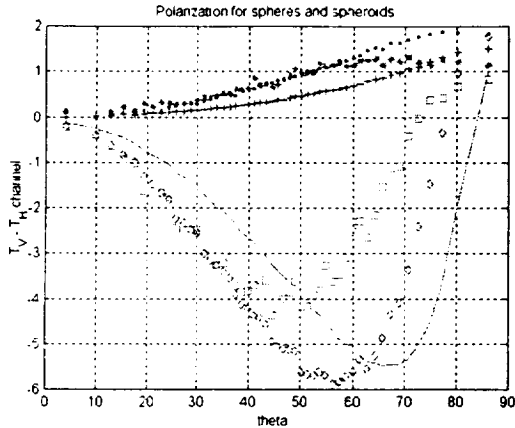


Figure 3: Same as fig.2 for downward polarization.

In the case of the non-spherical particles, the effect is significantly stronger and positive upward while negative in the downward direction.

With Fresnel surface the polarization pattern is complicated by the presence of the polarized surface. In this framework, however, Monte Carlo procedures are very useful because they can suggest which percentage of the signal is coming from the surface.

To better understand the polarization behavior we have studied in detail a particular situation (RR=20 mm/hr, Lambertian surface) by looking at the contributions to the polarization signal coming from different orders of scattering (fig.5).

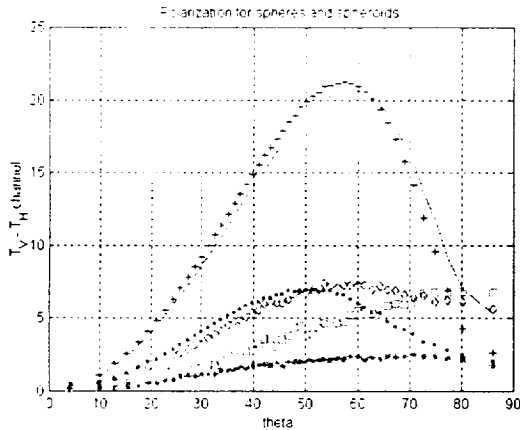


Figure 4: Same as fig.2 for Fresnel surface.

Without scattering the polarization signal is much lower in intensity and positive both upward and downward; in the upward direction the polarization is most

pronounced at small angles because of the preferentially nadir-oriented photons coming from the surface. In this case, since no scattering is involved, the mechanism of polarization is essentially driven by angular dependent absorption coefficient. The polarization signature then becomes more and more evident as one moves off nadir. This is due to the decrease in the ratio between vertical and horizontal extinction coefficients.

Considering the first order scattering events only, losses in intensities become less pronounced while a significant decrease in the polarization occurs both in the upward and downward directions. Downward, where a significant contribution comes from scattered photons, the decrease is so pronounced that the signal becomes negative for a great part of the angular range. Scattered photons are therefore preferentially H-polarized. This is not due to the scattering itself (that is, to the phase matrix) but mostly to the fact that interacting photons are preferentially H-polarized ( $K_{ext,H} > K_{ext,V}$ ).

If photons having had two scattering events are taken in account, then the signal is practically completely saturated.

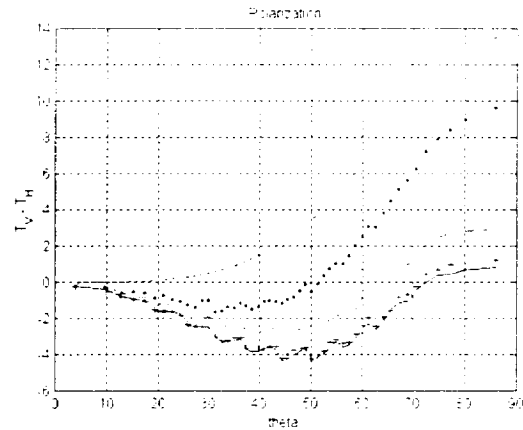


Figure 5: Different scattering order contributions to polarization downward: dotted, dashed and + line corresponds to 0,1,2 order; continuous line is multiple scattering solution and •line is solution without surface photons.

The effect of finiteness is studied by taking a 15x15 km horizontally extending cloud with the same physical properties as before. Temperatures are computed directly above the cloud, looking at  $\phi=0$ .

In figs. 6-7, the 20-mm/h Fresnel surface case is analyzed. The results of finiteness is a net depression in intensity both upward and downward (not shown). This is as expected because of the leakages from the sidewalls and the contributions from the colder water surface.

On the other hand, upward polarization shows a much greater signature than for infinite cloud for the same reason: now the sensor is seeing much more polarized contributions from surface than before. This explains why negatively polarized signals from perfectly oriented raindrops are much more attenuated than for the infinite case.

For Lambertian surface (not shown), contributions from the non-polarized surface and leakages from the sidewalls will tend to smooth the polarization signal from cloud and to broaden it over a region larger than the top of the cloud itself.

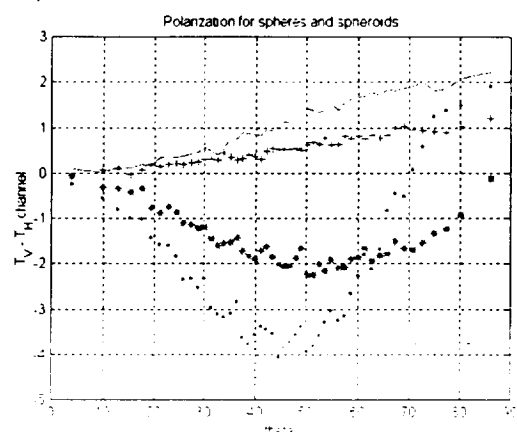


Figure 6: Downward polarization for finite (\* line is for perfectly oriented spheroidal droplets, + line for spherical droplets) and infinite raining cloud (dashed line is for perfectly oriented spheroidal droplets, dotted line for spherical droplets)

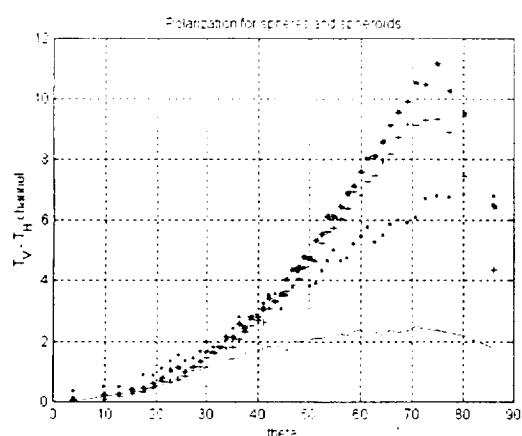


Figure 7: Same legend as fig. 6 for upward polarization.

Studies are now in progress to better understand the role of finite horizontal dimension and to find distinctive signatures of microphysical properties in water, ice and mixed phase clouds containing perfectly oriented particles.

#### Acknowledgements

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